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Small Systems: Single Electronics/Quantum Transport

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a. Summary of Work Accomplished

(i) Quantum Transport

Hu and myself rapidly completed our direct work in this area which led to a paper dealing with boundary effects in semiconductor quantum wires [1)][Here and elsewhere, reference numbers are to the papers listed in Section d below]. Our theoretical work led to very good agreement with the experimental work of Smith et al. (Phys. To-day 43, 24, 1990).

I also collaborated on the problem of magnetophonon resonances in quasi-one-dimensional wires with Dr. Ryu,[11)] a visitor from Korea (supported mostly with Korean funds with a small supplement from LSU) who was a member of our group from Jan. 1993 until Jan. 1994. This is a relatively new area of research both theoretically and experimentally and we are still waiting for experimental results pertaining to our work. In collaboration with Hu, a new dimension was added to such studies by consideration of a magnetic field[14)] and, in particular, we showed that the direction of the magnetic field plays a significant role in determining the relaxation rates and the magnetoconductivity related to the magnetophonon resonances.

(ii) Single Electronics

This has been the underlying theme of most of our research. This subject is of interest for both basic and technological reasons and it is now well-recognized that many interesting quantum phenomena come into play in the so-called mesoscopic regime.

Small tunnel junction (STJ) and small Josephson junctions (SJJ) lie at the heart of SE. Because of phase coherence across the junction, an analysis of the latter is easier in some respects. Thus we concentrated our initial efforts on an analysis of the experimental results of the Harvard group. Our first paper used a dissipative quantum tunneling model developed by Ford, Lewis and O'Connell to calculate the low-voltage resistance in small Josephson junctions[2)] and good agreement was obtained with experiment.

Next, we turned to a consideration of the fundamentals of Bloch oscillations in SJJ and we developed a new and enlightening approach[9)] based on our successful efforts to obtain an analytic solution (Eqs. (5) and (6) of Ref. 9) of the basic equation of motion of Likharev and Zorin. Our assumed bias current contains both ac and dc parts (Eq. (3)) and the limit of only dc ($I_A = 0$) gives in effect a lucid and rigorous

derivation of a well-known result for the Bloch oscillation frequency with damping effects included (Eq. (9)). Also, the weak-damping limit of our general result leads to our Eq. (14) which, in turn, in the limit of only dc current bias ($I_A = 0$), leads to the well known $I = 2e/t_B = 2ef_B$ result for the frequency of Bloch oscillations. (This result also follows from the $R_J \to \infty$ limit of our Eq. (11)). Furthermore, our analysis of phase-locking (see discussion in paragraph after Eq. (26)) leads to conclusions different in some respects than those appearing in the literature.

Leaving aside SJJ, we next turned to an analysis of the experiments of the Berkeley group which dealt with environmental effects on the Coulomb blockade in normal-metal STJ. By taking into account dissipation in the junction itself we were able to obtain much better agreement with experiment.[3] Of particular significance is the fact that we were able to explain the flattening off of R_o (the zero-bias resistance) at low temperatures (see discussion in last paragraph of Ref. 3).

Progressing beyond the realm of single junctions we then considered the experiments of the MIT group on two STJ where the island between the two capacitances is a semiconductor quantum dot. Notable features of the experiments are the conductance oscillations and the Coulomb staircase. Since the low temperature behavior of the conductance peak heights and widths could not be understood within existing theory, we extended the latter to incorporate environmental effects[16] due to the leads etc., which in turn cause fluctuations in the junction charges. This enabled us to explain many of the puzzling features in the MIT data.

Many investigators have shown that more precision can be attained in the investigation of SE effects by utilizing an array of junctions since this tends to block the generally unwelcome environmental effects. This motivated us to develop a general analysis of the electrostatic problem of a zero-temperature multi-gated small junction system.[10] In particular, we obtained the conditions for which Coulomb blockade is operative (Eqs. (2.11), (2.14) and (2.15) of Ref. 10).

Next, in collaboration with Ryu, Hu and I analyzed quantum fluctuation effects in a single electron box by considering the gate voltage fluctuations with the use of the quantum Langevin model.[12] At $T = 0$, we derived an analytic expression for the junction charge as a function of the gate voltage and its fluctuations, and showed that the sawtooth shape of the junction charge, as predicted by existing theories, is rounded off by the quantum fluctuation effects. At finite temperature, the theory was compared with the experiments of Lafarge et al., and a good fit was obtained at all the relevant temperatures.

Our next project was an ambitious undertaking which is still ongoing viz. the development of a nonperturbative calculation of Coulomb blockade in a small tunnel junction.[13] We made use of the closed-time-path Green's function and Odintsov's polaron formulation. Self consistent forms for the current-voltage (I-V) characteristics, the damping function, the fluctuation function, and the non-equilibrium Bose distribution function, were obtained. At T = 0 and in the weak dissipation limit, analytic results could be obtained. In particular, we showed that the widely used Ohmic approximation (tunneling impedance $Z(\omega)=R_T$) for the effect of dissipation on Coulomb blockade, is satisfactory in the range of $R_T \sim R_k$ to $10R_k(R_k=25.8k\Omega)$. More extensive work remains to be carried out in this area.

Hu and I next considered a problem of theoretical interest[15] and we showed that, in the weak coupling limit, the main formalism of the phenomenological quantum Langevin model for single electron tunneling in small tunnel junctions is derivable within the framework of the rigorous generalized Landauer formula.

Our emphasis again shifted, this time to a consideration of charged solitons and it led to a paper[17] which perhaps gave us the most personal satisfaction because we first had to invert analytically a non-trivial infinite-dimensional tridiagonal matrix. This enabled us to obtain an exact solution for the single charge soliton, in a one-dimensional array of N gated junctions with equal junction capacitances C and equal gate capacitances C_g. Analytical expressions for the total energy, as well as the injection threshold voltage of a charge soliton in a biased array, were derived. Based on the exact solution, we analyzed the effects of N and C_g / C on the charge soliton, to provided an understanding of the existing experiments. Of further significance is the fact that our techniques are clearly applicable to a variety of not only other single charge tunneling problems but also problems in other areas of physics.

(iii) Dissipative Problems in General

Whereas the main thrust of our overall work could be described as:

(a) keep in close contact with the experimental results;

(b) concentrate on issues and experiments of relevance to the development of innovative devices of possible interest to ONR; we felt that these goals could be optimized if we also endeavored

(c) to continue to do research on fundamental issues pertaining to our studies on dissipation.

With that goal in mind, I continued my long-time collaboration (extending over 20 years) with Professor G. W. Ford, University of Michigan. First of all, motivated by the calculation of Manilou and Kittel on the high temperature classical ensemble average of the nonequal time product of the displacement and random force in the Brownian motion problem, Ford and O'Connell in collaboration with O'Connell's student (Li) generalized these considerations to the quantum case and to the case of a arbitrary heat bath.[8] In addition, because of their fundamental importance in dissipative studies in general, they also considered other correlation functions. Finally, because their paper was being published in the American J. of Phys., they welcomed the editors suggestion to present a mini-review of the area with some emphasis on applications.

Ford and O'Connell(FOC) also brought to a successful conclusion their studies of the case of a blackbody radiation heat bath (which we refer to as the "rosetta-stone" of heat bath models because the Hamiltonian for the problem is known, being the universally accepted Hamiltonian of non-relativistic quantum electrodynamics). Two noteworthy results emerged from this work viz.[6,8]

(1) the solution of the well-known problem of "runaway solutions"

(2) that the electron must be considered to have a non-zero radius, of the order of the classical radius. In essence, FOC showed that the Abraham-Lorentz equation for the radiating electron emerges from their work if one assumes (incorrectly) that the electron is a point particle. It is this deficiency in the Abraham-Lorentz (AL) equation which leads to "runaway solutions". Instead, FOC obtained a new equation which has many striking features:

(a) It is a simple second-order equation (in contrast to the AL equation which is third order).

(b) It has well-behaved solutions (in contrast to the runaway solutions of the AL equation).

(c) In the absence of an external force $f(t)$ it reduces to Newton's equation for a free particle (a property lacking in the AL equation).

(d) It implies a modification in the Larmor formula

(e) The radius of the electron cannot be greater than about r_0 (the classical radius of the electron). A relativistic extension has also been carried out.[5]

Another question of general interest is how energy balance is affected by the presence of an environment, which was the subject of Ref. 7. One point stressed in this paper is the fact that, at equilibrium, the energy lost by a quantum particle due to the frictional (dissipative) force is balanced by the work done on the particle by

the fluctuation force. Finally, in Ref. 4, a generalization of our theoretical framework to the case of a "squeezed environment" was considered.

In summary, most of the goals originally proposed were achieved but work still remains to be completed on some projects (notably the problem considered in Ref. 13). In addition, as so often happens, various unforeseen and unexpected results were obtained, the most noteworthy being the techniques developed in Ref. 17 as they should be applicable to a variety of other single charge tunneling systems.

b. **Graduate Students Supported under the Grant**

None

c. **Postdoctorals Supported under the Grant**

Gen-you Hu. He has been working with me since May 1986 and is still working with me, now as a Senior Postdoc.

d. **Papers Published in Refereed Journals/Books**

1. G. Y. Hu and R. F. O'Connell, "Inhomogeneous Boundary Effects in Semiconductor Quantum Wires," J. Phys. Condensed Matter 4, 9623(1992)

2. G. Y. Hu and R. F. O'Connell, "Low Voltage Resistance in Small Josephson Junctions.", J. Phys. Condensed Matter 4, 9635(1992).

3. G. Y. Hu and R. F. O'Connell, "Charge Fluctuations and Zero-Bias Resistance in Small Capacitance Tunnel Junctions", Phys. Rev. B, 46, 14219(1992).

4. R. F. O'Connell, "Dissipation in a Squeezed-State Environment", Invited Paper in NASA Conference Publication 3219, Proc. of the "Second International Workshop on Squeezed States and Uncertainty Relations", Moscow, Russia, May 1992.

5. G. W. Ford and R. F. O'Connell, "Relativistic Form of Radiation Reaction", Phys. Lett. A 174, 182(1993).

6. R. F. O'Connell, "Does the Electron have a Structure?", Invited Paper honoring Professor A. O. Barut, special issue of Foundations of Physics 23, 461(1993).

7. X. L. Li, G. W. Ford, and R. F. O'Connell, "Energy Balance for a Dissipative System", Phys. Rev. E, 48, 1547(1993).

8. X. L. Li, G. W. Ford, and R. F. O'Connell, "Correlation in the Langevin Theory of Brownian Motion", Am. J. Phys., 61, 924(1993).

9. G. Y. Hu and R. F. O'Connell, "Bloch Oscillations in Small Capacitance Josephson Junctions", Phys. Rev. B 47, 8823(1993).

10. G. W. Hu and R. F. O'Connell, "Coulomb Blockade in Multi-Gated Small Junction Systems", J. Phys. Condensed Matter 5, 7259(1993).

11. J. Y. Ryu and R. F. O'Connell, "Magnetophonon resonances in quasi-one-dimensional quantum wires", Phys. Rev. B, 48, 9126(1993).

12. G. Y. Hu, R. F. O'Connell and J. Y. Ryu, "Quantum Fluctuation Effects in a Single Electron Box", Proceedings of the XX International Conference on Low Temperature Physics, Eugene, OR, Aug. 1993, Physica B 194-196, 1021(1994).

13. G. Y. Hu, R. F. O'Connell and J. Cai, "Nonperturbative Calculation of Coulomb Blockade in a Small Tunnel Junction", Proceedings of the XX International Conference on Low Temperature Physics, Eugene, OR, Aug. 1993, Physica B 194-196, 1023(1994).

14. J. Y. Ryu, G. Y. Hu and R. F. O'Connell, "Magnetophonon Resonances of Quantum Wires in Tilted Magnetic Fields", Phys. Rev. B, 49, 10437(1994).

15. G. Y. Hu and R. F. O'Connell, "On the relationship between the quantum Langevin model and the Landauer formula", Phys. Lett. A 188, 384(1994).

16. G. Y. Hu and R. F. O'Connell, "Langevin Equation Analysis of a Small Capacitance Double Junction", Phys. Rev. B 49, 16505(1994).

17. G. Y. Hu and R. F. O'Connell, "Exact Solution for the Charge Soliton in a One-Dimensional Array of Small Tunnel Junctions", Phys. Rev. B 49, 16773(1994).

e. **Abstracts Presented at March Meetings of the American Physical Society and Published**

1. R. F. O'Connell and G. Y. Hu, "Low Voltage Resistance in Small Josephson Junctions", Bull Am. Phys. Soc., 37 (1), 291 (1992).

2. G. Y. Hu and R. F. O'Connell, "On deviations from the Ambegaokar-Baratoff critical current for small Josephson junctions," Bull. Am. Phys. Soc., 37 (1), 380 (1992).

3. G. Y. Hu and R. F. O'Connell, "Environmental Effects on Coulomb Blockade Oscillations in the Conductance of a Semiconductor Quantum Dot", Bull. Am. Phys. Soc. 38(1), 641(1993).

4. R. F. O'Connell and G. Y. Hu, "Noise Effects on Coulomb Blockade and Zero-Bias Resistance in Small Capacitance Tunnel Junctions", Bull. Am. Phys. Soc. 38(1), 697(1993).

5. G. Y. Hu and R. F. O'Connell, "Exact Solution for the Charge Soliton in a One-Dimensional Array of Small Tunnel Junctions", Bull. Am. Phys. Soc. 39(1),74(1994).

6. R. F. O'Connell and G. Y. Hu, "Single Electron Box: A Quantum Langevin Model Study", Bull. Am. Phys. Soc. 39(1), 189(1994).

7. Y. L. He, G. Y. Hu and R. F. O'Connell, "The Structure and Properties of Nano-Size Crystalline Silicon Films", Bull. Am. Phys. Soc. 39(1), 686(1994).

f. **Honors for Grant Employee (R. F. O'Connell)**

1. "Quantum Langevin Equation Approach to a Variety of Dissipative Problems in Physics", 3 invited lectures given at the University of Ulm, Germany, June 30 and July 7, 14, 1992.
2. "Quantum, Noise, and Dissipative effects in Mesoscopic Systems", invited lecture given at the 23rd Winter Colloquium on Quantum Electronics, Snowbird, Utah, Jan. 1993.
3. I accepted an invitation to Lyngby/Copenhagen, Denmark during July 1994 to give lectures on dissipative processes in general but with special emphasis on the potential application of our techniques to problems in Chemical Physics (as, for example, the influence of a molecular environment on chemical reactions). I interacted at length with many scientists and presented the following formal lectures:
   (a) "Generalized Quantum Langevin Equation Approach to Dissipative Problems in Physics", Workshop on Concepts in Chemical Physics", Chemistry Department B, Technical University of Denmark, Lyngby.
   (b) "Dissipative and Fluctuation Phenomena in Quantum Mechanics with Applications".

   I also accepted an invitation to deliver a more general lecture on dissipation at the University of Aarhus.
4. I accepted an invitation to become a Board Member of Physics Review A for a 3-year term.